IMPROVEMENTS TO INTEGRATED HYDROLOGIC MODELING IN THE TAMPA BAY, FLORIDA REGION: HYDROLOGIC SIMILARITY AND CALIBRATION METRICS

Jeffrey Geurink, Water Resources Engineer, Tampa Bay Water, Clearwater FL, Geurink@tampabaywater.org; Ron Basso, Hydrogeologist, Southwest Florida Water Management District, Brooksville, FL; Patrick Tara, Senior Engineer; Intera Inc., Tampa, FL, ptara@intera.com; Ken Trout, Research Hydrologist, University of South FL, Tampa, FL, trout@eng.usf.edu ; Mark Ross, Associate Professor, University of South Florida, Tampa, FL, mross@eng.usf.edu

Abstract: The Integrated Northern Tampa Bay (INTB) model application was developed using the Integrated Hydrologic Model (IHM) simulation engine to improve hydrologic assessment capabilities in a 10,000 square kilometer region of west-central Florida. IHM uses the EPA HSPF model to simulate surface-water processes and the US Geological Survey model MODFLOW to simulate ground-water processes. With near simultaneous integration of HSPF with MODFLOW, IHM provides the ability to simulate hydrologic transitions that occur between deep (>2 meters) and near-surface (0-2 meters) water-table conditions which influence surface and groundwater processes. Compared to prior applications, the INTB model shows improvements in the dynamic response of hydrologic processes while using input data which is better constrained to physical measurements. Parameter estimation and manual calibration was used by employing quantitative metrics for streamflow, spring discharge, ground-water heads, depth to water table, temporal change in head and flow, and target ET. Qualitative metrics were developed for dry/flooded cells and various wet/dry stage metrics for water bodies. Quantitative metrics were applied using statistics for the mean, above and below the median, and within the high and low quartiles. Recent improvements in the dynamic response of the INTB model are the outcome of refinements to the simulation engine, enforcing hydrologic similarity principles within discretization units, constraining the model with average annual ET targets, and applying the calibration metric of depth to water table.

INTRODUCTION

The local water supply agency for the west-central Florida area, Tampa Bay Water (TBW), and the local state regulatory agency for surface water and groundwater resources, the Southwest Florida Water Management District (SWFWMD), commissioned the development and application of an integrated surface-water/groundwater model to gain an increased understanding of the regional surface and groundwater flow systems and to assess the impacts of water-supply wellfield pumping. The public-domain model developed from this effort, the Integrated Hydrologic Model (IHM), is a combination of the EPA surface-water model HSPF (Bicknell et al., 2001) and the US Geological Survey groundwater model MODFLOW96 (Harbaugh and McDonald, 1996). This paper describes the application of IHM to a 10,000 km^2 area of west-central Florida.

The surface and groundwater hydrology of the model region is diverse. More than 50% of the region experiences near-surface water table conditions on an annual or more frequent basis. Average annual rainfall is 52 inches and evapotranspiration (ET) accounts for approximately

70% of annual outflow. Land cover is varied including urban, grassland, forest, agricultural, mined land, water, and wetlands. These general land classes were used to discretize the model domain into hydrologically similar units. To constrain the model, target values of average annual ET were developed as a calibration metric for each general land class. Many rivers traverse the model domain with stream flow varying from less than five to more than 15 inches per year. The hydrogeology of the region includes an unconsolidated surficial aquifer, predominantly acting as a reservoir for baseflow to water bodies and recharge to the underlying Floridan aquifer system. In most of the model domain, the carbonate Floridan aquifer is semi-confined, receiving recharge by means of leakage from the surficial aquifer; however, portions of the Floridan aquifer are unconfined receiving recharge directly as infiltration through the vadose zone. The presence of near-surface water-table conditions imposes significant interaction between surface and ground-water processes.

The boundaries of the Integrated North Tampa Bay Model (INTB) domain are primarily defined by the Gulf of Mexico and inland groundwater flow lines. After the INTB model boundaries were defined hydrologic, hydrogeologic, meteorologic, and GIS data were collected for the area. Because many of the datasets are large, much of the data is maintained and manipulated in databases. Microsoft Access was selected as the database application due to its wide-spread availability

<u>Integrated North Tampa Bay Model Domain</u>: The model domain is located in the west-central Florida region, bordered by the Gulf of Mexico on the west and extends east to the eastern boundary of the Southwest Florida Water Management District (SWFWMD). Tampa Bay is located in the southwest part of the domain (Figure 1). The north and east boundaries follow Floridan aquifer flow lines emanating at the Polk City high. As no useful flow lines exist at the southern portion of the model, a general head boundary was placed far enough from the areas of interest to minimize the boundary impacts.

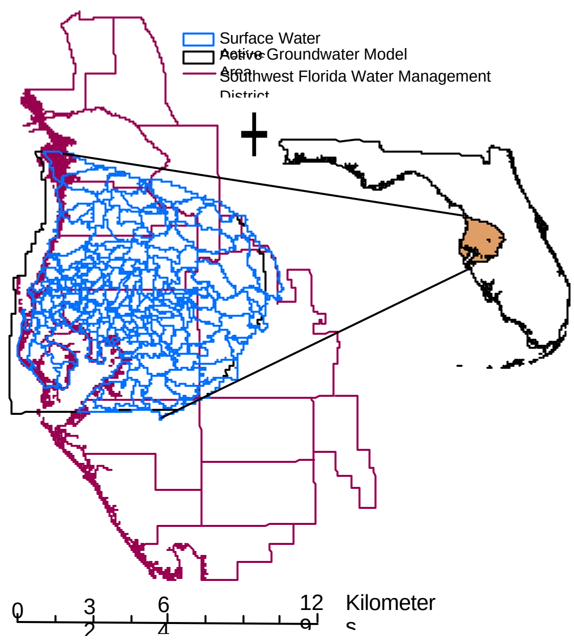

Figure 1 INTB model domain with surface-water basins.

DATA COLLECTION AND ORGANIZATION

Data requirements for a model application using the IHM include the combined requirements of the surface water and groundwater models plus data specific for integration. Temporal data for calendar years 1989-2000 were collected and organized for model input, calibration and validation. The data for each station were reviewed for errors and completeness. Types of errors are described within each data section.

Precipitation: Rainfall data were obtained at various time scales from three different sources: TBW, SWFWMD, and NOAA. Daily NOAA, TBW and SWFWMD rainfall data were used for refined spatial coverage. Rainfall at 15-minute frequency were obtained from NOAA. The daily rainfall data from SWFWMD were predominately volunteer data collectors that read standard volumetric rain gages. This data are prone to errors. However, the 236 SWFWMD daily rainfall stations represent the best spatial resolution available. Only 6 NOAA 15-minute data stations were available in the model domain. By averaging all available rain data for each basin on a daily basis the best volume is obtained for modeling.. This averaged daily volume for each basin was then disaggregated into a fifteen-minute time-series for use by the hydrologic model. The disaggregation was performed using the temporal distribution found at the nearest fifteen-minute station that had a similar (+/- 50%) daily total rainfall. If no NOAA 15-minute station fit these criteria, standardized distributions were used. The developed rainfall time-series for each basin was stored in a model binary data format (WDM) for use by HSPF.

Stream Flow and Baseflow Separation: Detailed land-use mapping was available from SWFWMD. The land-use maps provided the basis of the river system; land coded as open water or wetlands were treated as rivers. The land-use codes provided a very detailed river network. Because the land-use GIS coverage consists of polygons, areas of the river segment polygons were available through a GIS procedure. The MODFLOW conductance term, grid-cell river length x grid-cell river width x river bed hydraulic conductivity / river bed thickness, can be simplified by substituting the GIS-derived, grid-cell river area for the river length x width term. The MODFLOW river calibration was simplified to calibrate only the bed leakance term (river bed hydraulic conductivity / river bed thickness, K'/b').

To separate the main river channel from the surrounding wetlands areas, the line-based river coverage from the USF Southern District model (Geurink et al., 2000) was intersected with the new polygon-based river coverage. Polygons that were intersected by the line coverage were assigned the river order from the Southern District model. The resulting river coverage included wetlands surrounding the rivers, the main river channel with an associated order, lakes and reservoirs, and isolated or conditionally-connected wetlands.

MODFLOW, a finite-difference model, works with average parameter values within a grid cell. Elevation data is averaged over a grid cell and MODFLOW calculates an average head within a cell. The force driving water into or out of a river is the head gradient between the river and the surrounding aquifer. If a grid cell contains significant topographic relief, the local elevation of a river segment may differ substantially from the average elevation of the grid cell. The local aquifer head may also differ substantially from the average head within the grid cell. The object of elevation shifting is to restore the same gradient between the local river segment and the local aquifer head as exists between the average topographic elevation and the average head of the grid cell. Details of the elevation shifting procedure may be found in Geurink (2000).

Baseflow separation is a process that estimates the groundwater contribution to the total stream flow. For this project, the separation technique developed by Perry (1995) and utilized extensively in west-central Florida by the University of South Florida CMHAS and SWFWMD was employed. The technique is simply a numerical low-pass filter and works with a window of characteristic time length, in this case 121 days. The 121 days represents a time span of 60 days prior to a specified date, the specified date, and 60 days after the specified date. The result is a smoothed time series of minimum flows, the assumed baseflow. With the model calibration and period of interest beginning on 1/1/1989, flow measurements beginning on 9/3/1988 were necessary. Stream-flow measurements were available at 38 USGS gaging stations in the model area. Baseflow separations were performed at each of the 38 stations.

Aquifer Water Levels: Aquifer monitoring well data were initially obtained from SWFWMD and the USGS for the 12 year period of January 1, 1989 through December 31, 2000. The USGS provided two sets of data, one set of continuously monitored wells and another set of periodically monitored wells, primarily wells used in the semi-annual potentiometric surface inventory. The SWFWMD and the USGS data were combined into a single database. Where duplicate well records existed, as identified by the same well number, the source with the longest period of record was selected.

After the well records were processed, 1,479 observation wells distributed throughout the model domain were present. The observation well network consists of 783 surficial observation wells (Figure 4) and 696 Floridan observation wells. Many of the observation well are concentrated in the vicinity of the wellfields, this is particularly true of the surficial observation wells.

Spring Discharge: Daily spring discharge estimates were obtained from the USGS for Sulphur Springs and Weeki Wachee Springs. Sulphur Springs' data were available for the entire period of record, Weeki Wachee data began in late 1993. The USGS collects periodic discharge measurements for Crystal Springs. The periodic discharge records were linearly interpolated to produce daily discharge estimates for the entire period of record. Periodic discharge measurements for Lithia and Buckhorn Springs were obtained from SWFWMD. These periodic measurements were also linearly interpolated to produce daily discharge estimates for the entire period of record.

Well Pumping: Average monthly pumping rates for wells within the model area were secured from the SWFWMD SAS database. SWFWMD maintains records for high-volume extraction wells in the District. The records consist of metered wells where the actual water use is recorded, and estimated wells where water use is estimated based on a number of parameters. Low-volume residential wells are not included in the database.

A total of 7,613 wells are located within the boundaries of the surface water model. Because the boundaries of the groundwater model are slightly smaller than that of the surface water model, 7,470 wells were included in the groundwater model.

Basin Selection and Classification: The surface-water basin delineation originated from the USGS drainage basins from the 24,000 scale quadrangles. These basins were first modified to terminate at the USGS gauging stations selected for model calibration. Terminating the basins at the calibration gages is required to accurately determine the contributing area. The basins were further subdivided to better represent homogeneous areas of depth to the water table and land use/land cover. The basins were also modified to reflect smaller segments around wellfield areas. The wellfield areas reflect regions with possible impacts of pumping stress and hydrologic variability as a consequence of changes in depth to water table that have occurred or can occur in the future. The resulting basin coverage of the INTB domain contains 172 sub-basins. Each basin was divided into seven different land segment types defined by five general land-use categories. Each land segment represents an aggregate of separate land-use polygons or fragments within each basin. The separate fragments that comprise a land segment within a basin are assumed to possess hydrologic similarity. Splitting the basins where appropriate and using land segments reduces the range in hydrologic and hydraulic properties of the surface water system, which allow average model parameters to better represent hydrologic behavior for seasonally-varying and extreme conditions. Two additional general land-use codes, open water and wetlands, define the extent and location of reaches for HSPF.

Land Use: GIS land use coverages were obtained from SWFWMD. These coverages delineate areas of particular land use as classified by the Florida Land Use and Cover Forms Classification System (FLUCCS). There are 53 unique FLUCCS-coded land uses present in the model domain. The 53 FLUCCS codes were reduced to seven hydrologically unique classifications referred to as land segments.

Hydrography Selection and Classification: Hydrography represents all of the open water and wetland features which account for 25% of the INTB model domain. Hydrography elements are important in both the surface-water and ground-water components of the integrated model. For the surface-water system, hydrography elements route surface flows downstream and represent the surface storage available to store direct precipitation, surface runoff, and ground-water discharge. Compared to the storage available from hydrography elements, interception and depression storage are minor but not insignificant. For the ground-water system, hydrography elements can be recharge sources to groundwater or can receive concentrated (springs) or diffuse groundwater discharge.

The best available spatial representation of hydrography or water bodies was the SWFWMD land-use and land-cover (FLUCCS) GIS database. The USGS National Hydrography Database (NHD), USGS 100,000 scale hydrography DLG, or the EPA's RF1 coverages were only resolved to the major rivers and lakes. The SWFWMD FLUCCS database defined the full spatial extent of the available hydrography storage found within each basin.

For the surface water system, HSPF reaches were used to represent the routing and storage functions of hydrography elements. In the INTB model domain, the routing and storage characteristics were represented by three classes of reaches which include routing, connected, and conditionally-connected. Generally, the main trunks of major rivers and the main channel of significant tributaries of major rivers are classified as routing reaches which receive water from connected reaches or upstream routing reaches. Reaches that are classified as connected or conditionally-connected also function as routing features in the model. However, a primary function of these reaches is to store and attenuate surface runoff. Connected reaches have a direct connection to the final outfall.

Connected reaches were first identified by intersecting the reach polygons with the USGS 100,000 scale hydrography coverage. Then, reaches which shared boundaries with the first set of connected reaches were selected. Successive iterations of shared boundary reach element selections were performed to define all the directly-connected hydrography elements. Manual manipulation was also used to both speed the process and connect reach elements that were left disconnected by a road-crossing present in the FLUCCS layer or ditching that is not present in the FLUCCS layer.

The result is a comprehensive layer that contains hydrography elements (polygons) classified into three groups of reaches: routing (by definition connected), connected storage attenuation reaches, and conditionally-connected storage attenuation reaches. The proportion of surface runoff within a basin assigned to connected or conditionally-connected reaches was assigned based on the proportion of surface area of connected or conditionally-connected reaches within the basin. For example, if all the reach elements in a basin represented 100 acres and 30 acres of the reaches were found to be conditionally-connected, then 30% of the upland basin would be routed to the conditionally-connected reach. The remaining 70% of the upland basin would be routed, proportionate to surface area, to the connected reach in the basin and to any routing reach contained within the basin.

Target Evapotranspiration: Traditionally, hydrologic models have used one assumed ET rate for the entire model area ignoring the differences between developed areas, undeveloped areas, and areas dominated by wetlands. Due to limitations in ET data, this is often the long-term ET found from simple water budget analysis. To more reasonably distribute the ET burden across the model area and, thus, more appropriately constrain the model calibration, target ET rates were developed by basin and by land segment within each basin. The 53 FLUCCS codes within the model area were grouped into nine ET categories. Using the average depth-to-water table, most of the nine categories were subdivided into shallow water table (0-1 m), intermediate water table (1-2 m) and deep water table (> 2 m) classes. Target ET rates varied for each of the nine categories, except open water, and for the three depth to water table classes. The central Florida open-water ET rate was 55 inches per year (Geurink et al 1997) and the open-water category was assigned that rate. Wetlands were assumed to have a slightly reduced rate of 50 inches per year. ET rates for predominately grassed or forested areas were based on rates interpreted from results published by Zhang et al. (2001). The impervious fraction of urbanized land uses was assigned an ET target rate of 15 inches per year. This rate is an estimate of the abstraction capture and relies on the typical number and magnitude of central-Florida rainfall events annually. The high water-table rates were scaled down for the intermediate and deep water-table classes for all landforms, except open water.

RESULTS

The calibration of the model was aided by the parameter estimation software system PEST (Doherty, 2001). Links were incorporated into IHM to facilitate the use of PEST, which for models of this complexity, can be extremely useful. To aid in the evaluation of the calibration results, an application, the Display Tool, was developed which creates, organizes and displays a variety of graphs such as daily, monthly and seasonal stream and well hydrographs, weekly flow and head change, exceedence plots and cumulative flow plots. The Display Tool requires the use of Grapher software (Golden Software, www.goldensoftware.com) to create the individual plots. Figures 2-7 illustrate selected calibration results using the Display Tool. For all plots, the blue line is observed data and the red line is simulated data. The green line in Figure 7 is a simulated hydrograph that has been scaled to the land surface elevation in the same manner as the river cells were scaled in the MODFLOW river input package.

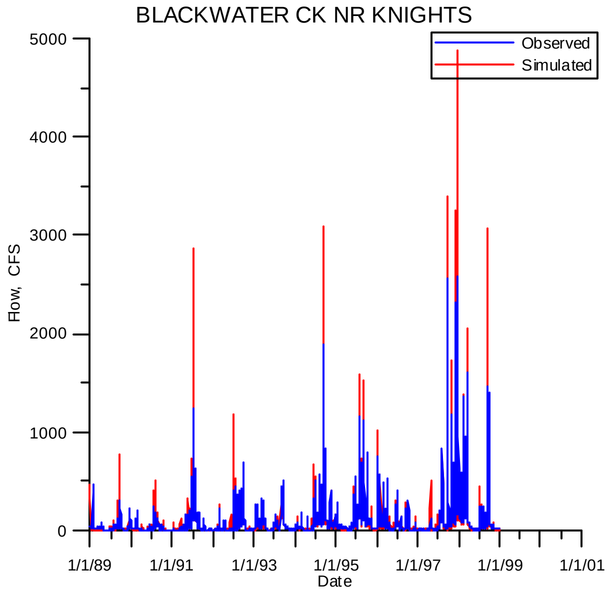

Figure 2 Ten-year daily hydrograph.

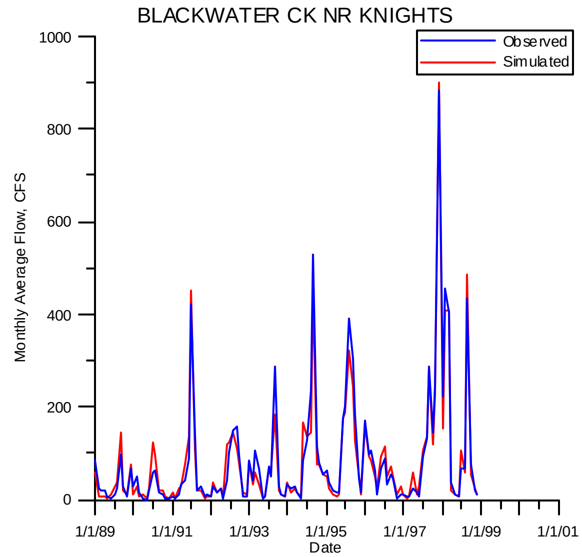

Figure 3 Ten-year monthly hydrograph.

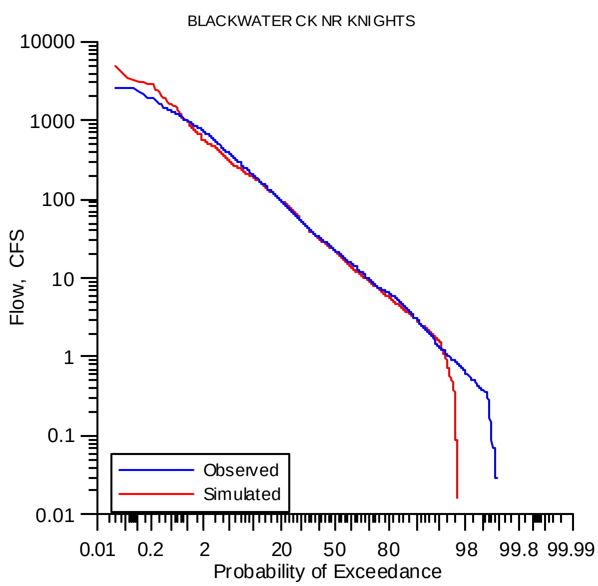

Figure 4 Exceedence Plot.

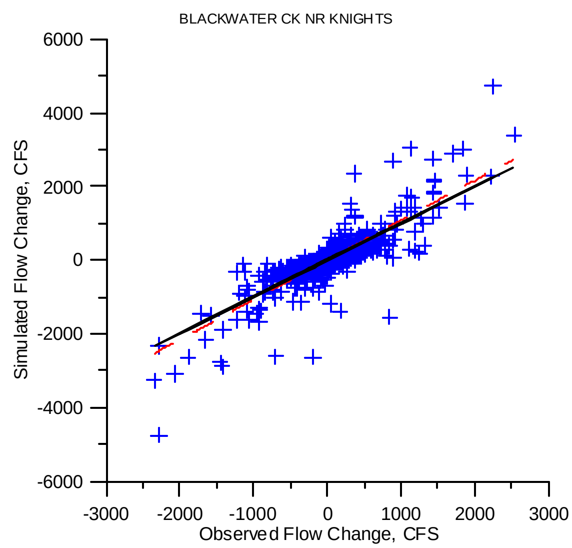

Figure 5 Seven-day flow change. Solid line is 45°, red dashed line is regression fit.

SUMMARY

The INTB model was the first large-scale application of IHM. Compared to prior applications, the INTB model shows improvements in the dynamic response of hydrologic processes while using input data which is better constrained to physical measurements. A combination of

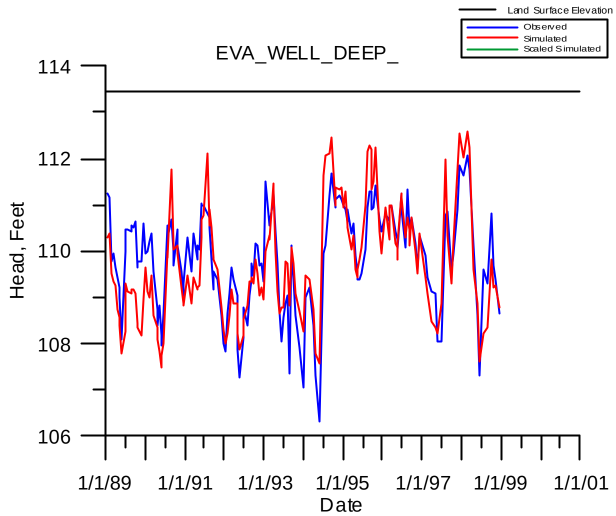

Figure 6 Ten-year deep-well hydrograph.

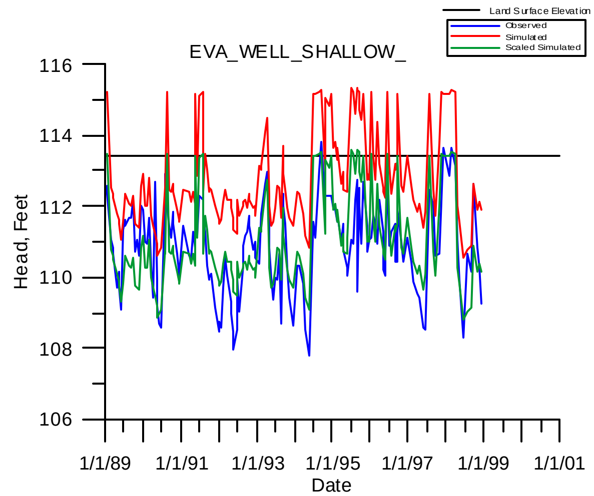

Figure 7 Ten-year shallow-well hydrographs.

parameter estimation and manual calibration was used by employing quantitative metrics for stream flow, spring discharge, ground-water heads, depth to water table, temporal change in head and flow, and target ET. Qualitative metrics were developed for dry/flooded cells and various wet/dry stage metrics for water bodies. Quantitative metrics were applied using statistics for the mean, above and below the median, and within the high and low quartiles. The Display Tool organizes and displays a variety of useful graphs to aid in the evaluation of calibration results. Recent improvements in the dynamic response of the INTB model are the outcome of refinements to the simulation engine, enforcing hydrologic similarity principles within discretization units, constraining the model with average annual ET targets, and applying the calibration metric of depth to water table.

REFERENCES

Doherty, J., (2001). PEST-ASP User's Manual. Watermark Numerical Computing, Brisbane, Australia.

Geurink, J. S., Nachabe, M., Ross, M. A., Tara, P. (2000). Development of Interfacial Boundary Conditions for the Southern District Ground Water Model of the Southwest Florida Water Management District, Prepared for the Southwest Florida Water Management District by The Center for Modeling Hydrologic and Aquatic Systems, Department of Civil and Environmental Engineering, University of South Florida, Tampa, Florida.

Geurink, J., Tara, P., Stewart, M. T., and Ross, M. A. (1997). A GIS-Based, Multi-Scale Integrated Model for Comprehensive Water Management Evaluations - Task Three Multi-Scale Ground Water Model Development And Simulation. University of South Florida, Tampa, Florida.

Perry, Robert Gerald, (1995). "Regional Assessment of Land Use Nitrogen Loading of Unconfined Aquifers," Ph.D. Dissertation, University of South Florida, Tampa, Florida.

Zhang, L., W. R. Dawes, and G. R. Walker. (2001). "Response of mean annual Evapotranspiration to vegetation changes at catchment scale." Water Resources Research. 37(3), pp 701-708.